Transforming the Short-term Sensing Stimuli to Long-term e-skin Memory

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***Abstract*—A Tantalum Pentoxide (Ta_2O_5) based resistive non-volatile memory device with bipolar switching behaviour was developed to demonstrate the new concept of memory in e-skin. The memory device showed stable switching behavior under pre-programmed voltage stimuli after an initial forming process. The memory cell was then integrated with a commercial tactile sensor with a new interface circuit, which enabled the switching of the memory cell through the electrical output from the sensor. This study provides a novel method for handling the transport and storage of large tactile data and will trigger advances towards memorable e-skin**

Keywords— e-skin; memory; tactile sensor; interface

I. Introduction

Electronic-skin (e-skin) capable of tactile imaging and quantification of the contact parameters such as temperature, pressure and texture, has attracted significant attention for applications such as robotics and prosthetics [1-5]. Various strategies have been explored over past two decades to develop e-skin with these capabilities. For example, sensors and transistors based on organic material have been demonstrated on polymer based flexible substrates. Benefiting from the intrinsic deformable properties of organic material, naturally flexible and stretchable electronic systems have been developed. Other well-studied methods include a mix of rigid, and flexible components integrated on flexible substrates. Irrespective of the technology, the current focus in the field of e-skin remains on the integration of multiple types of sensor and the improvement of mechanical deformability. Data recording and management over extended periods have seldom received any attention. For example, e-skin research has not explored human-skin like capacity to remember contact conditions over a period of time. The work presented here explores this new direction by considering e-skin with distributed memristors. With such integration strategy, the e-skin is able to not only detect the short term stimuli from external environment, but transform it to a long term information storage without power supply as well. We believe this work can enrich the study of e-skin and can be explored in the future for more potential applications in bionics [6, 7].

Memristors are electronic devices whose resistance depends on the history of electrical stimuli [8]. Among them, a metal/oxide/metal structure is one of the most studied device configuration for non-volatile memory applications with high endurance, long retention, fast operating speed, and potential compatibility to the complementary metal oxide semiconductor (CMOS) technology [9, 10]. Memristive devices have also been studied for artificial neural systems to mimic the behaviour of synapses [11]. Despite significant relevance, the conventional integration strategy via CMOS technology is not valid for e-skin application and other strategy has seldom been explored. In this work, we demonstrated a memristive device with a $Pt/Ta_2O_5/Ti$ structure interfaced with a commercial force sensitive resistor (FSR) based touch sensor. This system can be operated in "setting mode" and "resetting mode". In the setting mode, the memory was switched to an on state when the FSR was pressed to a fixed value. The state of the memory cell can be stored after retrieving the temporary stimulus from the force sensor. In resetting mode, the memory cell was switched to the off state by another stimulus. Thus, a transient input to the sensor can be written/erased in the form of long-term memory. This preliminary study will enrich the field of e-skin by triggering advances towards memorable e-skin.

II. Fabrication and Characterization

A. Memory device fabrication

$Pt/Ta_2O_5/Ti$ structure was used in this work for a memristive device. First, 40 nm Pt was deposited on a silicon wafer (with 300 nm thick thermal oxide) as the bottom electrode. Afterwards, 30 nm Ta_2O_5 was deposited by RF sputtering with a power of 300 W at room temperature. After defining the top electrode pattern using UV-photolithography, 10 nm Ti was deposited as the top electrode, followed by 20 nm Pt as an anti-oxidation layer. The device fabrication process was finalized after a standard lift off process. No thermal treatment was adopted. The schematic of the device structure is illustrated in Fig 1(a).

B. Memory device characterization

The Ta_2O_5 based memory has shown bipolar and unipolar switching behaviour depending on its combination with different electrodes [12, 13]. In this work, the virgin condition of the memory cell was the off state. After a 10 V forming process with 50 μA as compliance, the memory cell showed a bipolar switching behaviour with the Pt electrode grounded. The cell can be set stably to the on state under 6 V with 50 μA compliance and reset to the off state under -3 V (see Fig 1b). Retention and endurance tests were performed to characterize the memory device further. For the retention test, two memory cells were switched to the on state and off state respectively. The resistance in both states showed insignificant change after $5x10^4$ s as shown in Fig 1c. The endurance was tested in DC mode. The device showed a stable performance for 80 set and reset cycles (Fig 1d). It should be noted that the on/off ratio of the memory cell was purposely kept low by gentle set/reset electrical stimuli, in order to obtain a more stable switching performance. The memory window in the endurance test is

This work is supported EPSRC Engineering Fellowship for Growth – PRINTSKIN (EP/M002527/1).

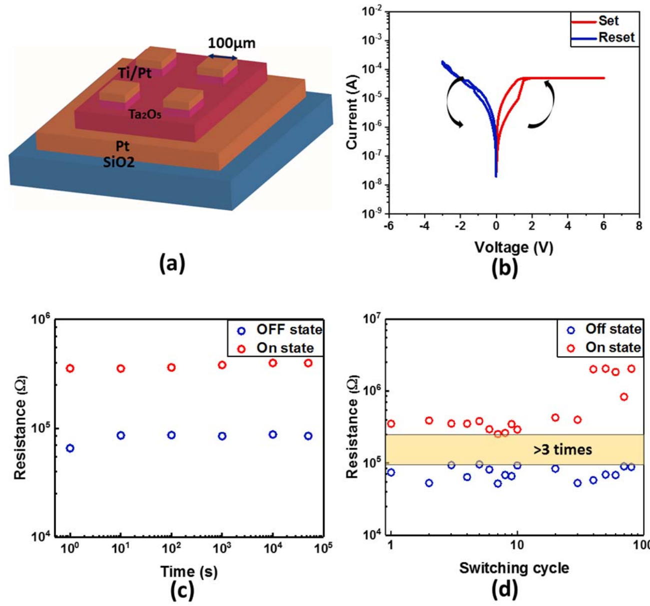

Fig 1: Characterization of a Ta_2O_5 based memory device. (a) Schematic of the metal-oxide-metal device structure; (b) typical set/reset curve, showing a bipolar switching nature; (c),(d) retention and endurance tests.

higher than 3. Practically, a memory device with a memory window of ~1.2 to 1.3 can be used if it is integrated with dedicated amplifying circuit, as a commonly adopted strategy in magnetoresistive random access memory [14]. The yield of the memory devices is around 50%. Others cannot be switched reliably. How to increase the device yield and device performance will be one of the focus in the future study.

C. *Sensor characterization*

A commercial FSR was used in this work for a proof of concept. Before integration, the output signal was characterized with different force inputs calibrated by a load cell. The initial reading of the FSR was higher than 2 GΩ (Open loop in multi-meter). This reading decreased from 193 kΩ to 62 kΩ when the force input was increased from 0.37 N to 0.59 N (Fig 2). The commercial sensor can be replaced by other custom sensors, which will be one aspect of future study. In this work, attention is focused on the interface between the sensor and the memory cell, as discussed in the next section.

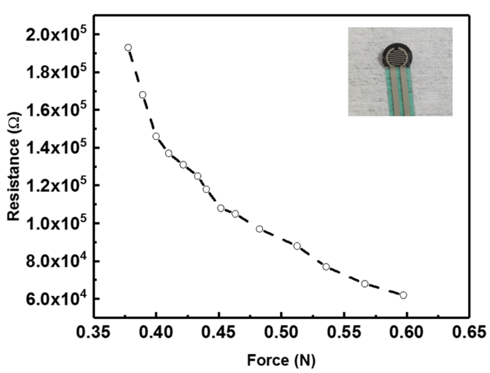

Fig 2: Characterization of the FSR showing the change of resistance as a function of applied external force. Inset: a photograph of the FSR used in this work.

III. INTERFACE BETWEEN MEMRISTOR AND SENSOR

Fig. 3 illustrates the schematic of the realized sensor memristor interface circuit. The circuit is divided into various blocks. The Tactile Sensing Block uses $OpAmp_3$ as a comparator where there are two voltage dividers. The FSR along with resistor R_{13} serves to convert the force input to a voltage output. This voltage is compared against the voltage across R_{12} of the voltage divider formed by R_{11} and R_{12}. As the force increases, the resistance of FSR decreases, which further drives the tactile stimulus output (Tact) to turn on. In the absence of a tactile stimulus, the Tact output from the Sensing Block remains low. Under this condition, the memristor node ***a*** is connected through the switching block to node ***b*** of the Readout Block via switches SW_2 and SW_8. $OpAmp_2$ serves as a comparator. Output from the two voltage dividers are compared-the first output for comparison is formed by the memristor and R_6 while the second is formed by the R_7 and R_{14}. To avoid altering the state of the memristor, the readout is carried out by supplying voltages ~10mV across the memristor. The voltage to the memristor-R_6 voltage divider is provided by the Readout Voltage Block. The Readout Voltage Block comprises of the resistor R_1 and Zener diode Z_1 (4.7 V), supplying a constant voltage across voltage dividers R_2 and R_3 and resulting in a net output voltage of 25 mV. $OpAmp_1$ works as a voltage follower. If the memristor is in the on state, the comparator $OpAmp_2$ drives the LED through Q_2 and R_9. Otherwise, the LED remains off. When the Tact stimulus reaches a high value, the memristor gets either set or reset, depending upon the condition of switches SW_3, SW_4, SW_5, SW_6 controlled by the SET/RESET (S/R) signal. Specifically, when the S/R signal is high, the switches SW_4 and SW_6 are ON resulting in the memristor being connected to the SET Block (setting mode). The purpose of the SET Block is to apply 6 V to set the memristor with current compliance. This compliance is given by (V_{Z2}-0.65 V)/R_5 (~50 µA), which is the testing condition mentioned in section II. When the S/R signal is low, the switches SW_3 and SW_5 turn on and the memristor connects to the RESET block (resetting mode). The RESET block is formed by the resistors R_{10} and Zener diode Z_3 which gives an output of -2.4 V across the memristor by the polarity reversal across the switches, thereby resetting the memristor.

The circuit was then implemented with the memory and FSR tactile sensor mentioned above and tested with a data acquisition board from National Instruments (NIDAQmX USB-6363) board in a differential read out mode. Force input was manually applied to the sensor (Fig 3). A LabView virtual instruments (VI) program was developed to monitor the voltage drop across the memristor and the voltage across R_{13} given by the FSR-resistor R_{13} voltage divider. As shown in Fig 4, in setting mode, when the force stimuli are applied to the FSR tactile sensor, the voltage across the FSR-resistor divider increases from 0 V to ~3 V. When it reaches a threshold, the Tact output turns on causing the memristor to get connected to the SET block through the switching block. This causes the voltage across memristor to rise from 0 to 6 V, setting the memory cell to the on state. Similarly, in resetting mode, the memristor receives a reset voltage of -2.4 V from the RESET block when a stimulus over a pre-defined threshold is applied to the FSR tactile sensor. The memory cell is therefore reset to the off state. This validates the working of the circuit through which sensory stimuli are converted into

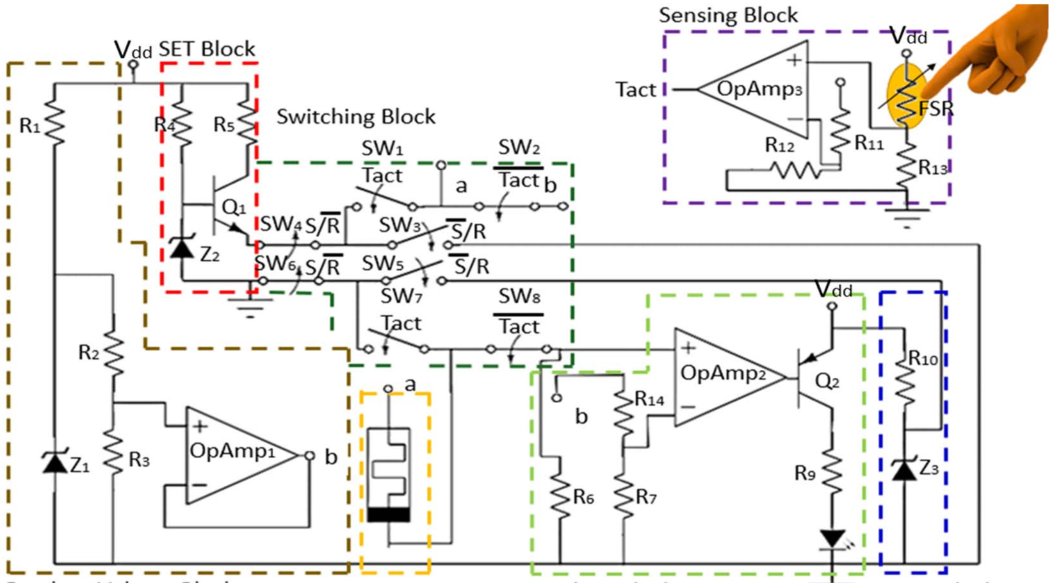

Fig 3: Schematic of the sensor-memristor interface circuit.

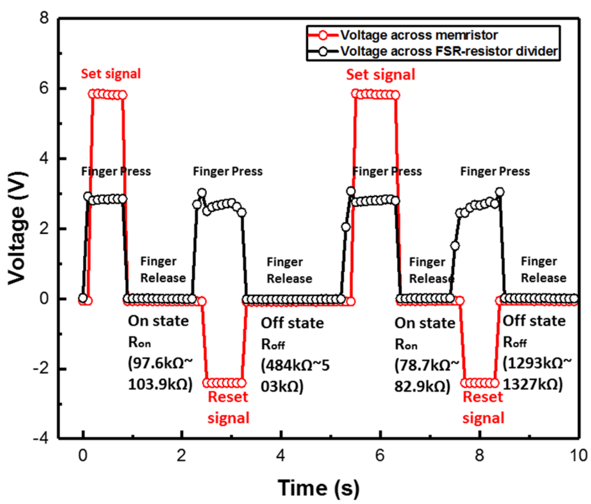

Fig 4: Transient output of the memristor-tactile sensor interface under press/release conditions showing set/reset of memristor.

long-term memory. Further study could involve an endurance test of the memristive device by programming force stimuli to the tactile sensor.

IV. Conclusion

The interface between a memristive device and touch sensor has been demonstrated to work well. The memory cell can be set and reset by signal input from the sensor and indicated by a LED. Thus, the transient stimuli to the sensor can be converted to non-volatile stored data in the memory cell. We believe this integration strategy can be used in e-skin for large tactile data handling over long-term use as in humans.

References

[1] C. Wang, D. Hwang, Z. Yu, K. Takei, J. Park, T. Chen, *et al.*, "User-interactive electronic skin for instantaneous pressure visualization," *Nat Mater,* vol. 12, pp. 899-904, 2013.

[2] M. L. Hammock, A. Chortos, B. C. K. Tee, J. B. H. Tok, and Z. Bao, "25th Anniversary Article: The Evolution of Electronic Skin (E-Skin): A Brief History, Design Considerations, and Recent Progress," *Advanced Materials,* vol. 25, pp. 5997-6038, 2013.

[3] C. G. Núñez, W. T. Navaraj, E. O. Polat, and R. Dahiya, "Energy-Autonomous, Flexible, and Transparent Tactile Skin," *Adv. Func. Mater.,* vol. 27, pp. 1606287-n/a, 2017.

[4] D.-H. Kim, N. Lu, R. Ma, Y.-S. Kim, R.-H. Kim, S. Wang*, et al.*, "Epidermal Electronics," *Science,* vol. 333, pp. 838-843, 2011.

[5] R. Dahiya, G. Metta, M. Valle, G. Sandini, "Tactile sensing—from humans to humanoids," *IEEE Trans. Robot.,* vol. 26, pp. 1-20, 2010.

[6] W. T. Navaraj, C. G. Nunez, D. Sakthivel, V. Vinciguerra, F. Labeau, *et al.*, Nanowire FET based Neural Element for Robotic Tactile Sensing Skin, *Frontiers in Neuroscience*, in press, 2017.

[7] W. Taube, F. Liu, A. Vilouras, D. Sakthivel, C. G. Nunez, *et al.*, "Nanowire FETs based Neural Network for Tactile Pattern Recognition in E-Skin," *BIOCAS 2016*, Shanghai, China, Oct 2016.

[8] D. B. Strukov, G. S. Snider, D. R. Stewart, and R. S. Williams, "The missing memristor found," *Nature,* vol. 453, pp. 80-3, May 1 2008.

[9] M. J. Lee, C. B. Lee, D. Lee, S. R. Lee, M. Chang, J. H. Hur*, et al.*, "A fast, high-endurance and scalable non-volatile memory device made from asymmetric Ta_2O_{5-x}/TaO_{2-x} bilayer structures," *Nat Mater,* vol. 10, pp. 625-30, 2011.

[10] K.-H. Kim, S. Gaba, D. Wheeler, J. M. Cruz-Albrecht, T. Hussain, N. Srinivasa*, et al.*, "A Functional Hybrid Memristor Crossbar-Array/CMOS System for Data Storage and Neuromorphic Applications," *Nano Letters,* vol. 12, pp. 389-395, 2012.

[11] S. P. Adhikari, C. Yang, H. Kim, and L. O. Chua, "Memristor Bridge Synapse-Based Neural Network and Its Learning," *IEEE Trans. Neural Networks and Learning Systems,* vol. 23, pp. 1426-1435, 2012.

[12] Y. Huang, R. Huang, Y. Pan, L. Zhang, Y. Cai, G. Yang*, et al.*, "A New Dynamic Selector Based on the Bipolar RRAM for the Crossbar Array Application," *IEEE Trans. Electron Dev.,* vol. 59, pp. 2277-2280, 2012.

[13] J. J. Yang, M.-X. Zhang, J. P. Strachan, F. Miao, M. D. Pickett, R. D. Kelley*, et al.*, "High switching endurance in TaOx memristive devices," *Appl. Phys. Lett.,* vol. 97, p. 232102, 2010.

[14] R. Waser, R. Dittmann, G. Staikov, and K. Szot, "Redox-Based Resistive Switching Memories – Nanoionic Mechanisms, Prospects, and Challenges," *Adv. Mater.,* vol. 21, pp. 2632-2663, 2009.